LCA Methodology

An Integrated Approach for Environmental Assessments

Linking and Integrating LCI, Environmental Fate Models and Ecological Impact Assessment Using Fuzzy Expert Systems

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Abstract

LCA is a system-wide assessment, and the LCIA phase is confronted with the difficulties of local and regional effects in a number of impact categories. We integrate three different environmental techniques to demonstrate how these effects can be addressed in an environmental assessment. The techniques are life cycle inventory, environmental fate models, and an ecological impact assessment using fuzzy expert systems.

Results of the LCI are mass and energy flows. In the environmental fate modelling step these mass flows are transformed into concentration and immission values by dispersion–reaction models. A generalised fuzzy expert system for the environmental mechanisms compares calculated exposure with site specific buffering capacities and formulates a generalised dose–response relationship. This generalised fuzzy expert system is used as a template for the assessment of local and regional environmental impacts. An application of this integrated approach is shown for a practical problem: production of magnesium car components. The environmental fate of nitrogen oxides which are released due to the major combustion source within that production system is simulated. Fuzzy expert models for crop damage, soil acidification and eutrophication determine the possible environmental impact of the immited nitrogen oxides.

The important methodological extension of this integrated approach is a regionalised impact assessment depending on the spatial distribution of environmental characteristics.

Keywords: Buffering capacity; dispersion-reaction model; environmental fate modelling; environmental impact assessment; exposure-response relationship; Fuzzy Expert System; LCA; LCI; LCIA; Life Cycle Assessment; Life Cycle Impact Assessment; Life Cycle Inventory; local and regional impacts; nitrogen oxides; NO_x; regionalisation; site dependence; source-receptor relationship

1 Introduction

Life Cycle Assessment (LCA) has widely been used over the last years as a tool for assessing the environmental aspects and potential impacts of products and services. While methodology is well developed for the steps goal definition and Life Cycle Inventory (LCI), the impact assessment is still under discussion (Umweltbundesamt, 1995; Pohl et al., 1996; ISO, 1997).

The Society of Environmental Toxicology and Chemistry (SETAC, 1993) called for the development of models which integrate the fate and impact of emissions in the assessment of the life cycle of products. There is also a need for expert systems which facilitate the step of impact assessment within LCA (SETAC & SETAC Foundation for Environmental Education, 1993). The German Federal Environmental Agency (Umweltbundesamt) requests that global and local impacts be considered within Life Cycle Impact Assessment (LCIA) (Umweltbundesamt, 1992). The SETAC LCA impact assessment work group asks for an integration of different techniques to conduct a more complete and holistic environmental assessment (SETAC, 1997). Suitable quantification parameters exist to calculate the potential environmental impact of emissions on a global scale such as global warming or tropospherical ozone depletion. Impact potentials like Global Warming Potential (GWP) or Ozone Depletion Potential (ODP) are already widely used in LCA.

The intensity of local and regional impacts, as for example acidification or eutrophication, depends on variable environmental conditions and is therefore *site dependent.* Hence, many authors, for instance Owens (1996), Tolle (1997) and Krewitt et al. (1998), state that the concept of global parameters is not useful for the LCIA of local and regional impacts. A research goal is then to develop and to evaluate suitable methods for assessing local and regional impacts within LCA.

2 Aim and Scope of the Study

Our intention was to develop a general model for an integrated approach of environmental assessment where LCI, environmental fate modelling and environmental impact assessment together can be used as a tool to assess local and regional impacts of emissions released along the life cycle of

products. The actual impacts at the point of emission for several impact categories ought to be addressed site dependent. This approach is distinct from the common, as it suggests a truly integrated approach. It reaches far beyond LCIA by the use of other environmental modelling techniques.

A prototype of this integrated approach has been developed and tested. This study was realised in co-operation with the Department of Environment and Transportation of Volkswagen AG, Wolfsburg and the Institute of Geoecology of the Technical University of Braunschweig.

The following section summarises the basic concept of the general assessment model while section 4 describes the prototypical realisation, an application and its results.

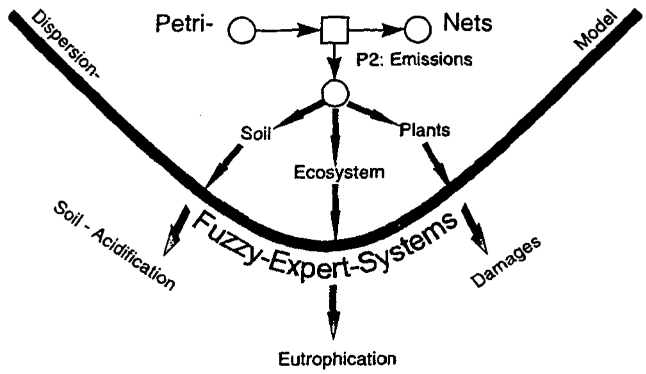

Fig. 1: Methodological concept of the integrated approach for life cycle assessment

3 Methodology

To meet the required extensions for a truly integrated approach, a general method was developed which consists of three modules. These are:

- Life Cycle Inventory
- environmental fate modelling comprising chemical reactions and the spatial spread of emissions
- a detailed environmental impact assessment based on the results of the previous step and realised by fuzzy expert systems, which allow an assessment of ecological impacts for several categories at one site involved in the system life cycle.

Figure 1 summarises this methodological concept: In the upper part of the figure the LCI phase is symbolised by a small Petri-Net which can stand for a section of a product life cycle. The environmental fate modelling is represented by the black arrows and the ecological compartment soil, ecosystem and plants which are placed below the Petri-Net. These environmental sinks can be identified as *receptors* of immissions. Soil, ecosystem and plants are understood as examples. They may be replaced by any other receptor whose potential impacts have either a regional or local spatial environmental sensitivity. The grey line symbolises the methodological boundary which is crossed between deterministic modelling and the application of soft computing-methods. Beneath this line, examples are shown for the environmental assessment of fuzzy expert systems. In this figure, these are soil acidification, eutrophication and plant damages. The uncertainty of the knowledge and the imprecision of the information increases from top to bottom in the figure.

3.1 Life Cycle Inventory

LCI was performed using the theoretical background of coloured Petri-Nets. The theory of coloured Petri-Nets is explained by Jensen (1992). Material and flow analysis are modelled by a network approach based on the coloured Petri-Nets. A Petri-Net is a bibartite graph with places (input, output), connections and transitions. Production and transport processes are identified with transitions. The transitions are the graphical representations of the mass and energy flow equations of the different processes. Storage places, products, raw material deposits and emissions are identified with places.
To undertake an LCI of a product, the sites of production are usually known (otherwise the transport distances could not be determined). We did not aggregate the same processes at different sites to unit processes, but designed the Petri-Net in a way that we could calculate the site specific mass flows of the stationary emission sources. When annual production chiffres are known for the studied product, the mass flow values can be transformed into mean annual in and output values. The site specific emissions or output sites define the interface between the LCI and the environmental fate modelling[1].

3.2 Modelling concept of environmental fate modelling

The environmental fate modelling enables the calculation of the spatial spread of emissions starting from the point of emission, providing the results as concentrations and immissions in space and time. It thus models the source receptor relationship. The environmental fate of emissions can be modelled by different approaches for the media soil, water or air. All dispersion models are based upon systems of differential equations (ordinary or partial) which contain terms for transport, chemical reactions and deposition processes.

The emission places from the LCI have to be localised geographically. Their mass flows are identified as sources in the context of a dispersion model. Output sites from the LCI may be mobile (e.g. transports) or stationary point sources (e.g. stacks) or diffuse inputs (such as nitrogen leaching out of agricultural sites). It depends on the observed process (in the transitions) of the LCI. Geographic Information Systems support these different types of information exchange from LCI results to reaction dispersion models.

Modelling the spatial spread of emission also depends on the observed media. Several modelling approaches exist for trans-

[1] There exists a lot of sophisticated programs supporting LCI, here the program Umberto® was used.

port modelling in atmosphere, water or saturated and unsaturated soil horizons. Seppelt (1997), for example, offered approaches for simulating the process of nitrogen loss due to agricultural production on a regional scale, based on simulation models of a different complexity.

It is useful to couple models for different media. The emitted substances pass from one medium to the other in most cases. Examples for coupled models of the different media are given in the context of an agricultural production concerning transport models in saturated and unsaturated soil horizons performed by Diekkrüger (1992).

A general overview of groundwater reaction dispersion models can be found in Baer & Verruijt (1987) and Anderson & Woessner (1992). A selection of available air pollution models is presented in Zanetti (1990), and an application can be found in section 4.2 of this paper.

3.3 Fuzzy-expert-systems for environmental assessments

The results of the environmental fate modelling are used for the assessment of the exposure of environmental compartments to a certain substance or burden. In our integrated approach, the assessment is performed by a fuzzy expert system which links the results of transport modelling and environmental receptors. It is described in the following section.

The first two phases of the integrated LCA approach, presented in the sections 3.1 and 3.2, describe physical and chemical processes which can be simulated by deterministic models. The ecological impacts of immissions are a result of complex interactions which can often be described by heuristic approaches alone (Kelly & Harwell 1989). Nevertheless, the causality between the exposure to a burden and the response of a receptor can often be described with expert knowledge. An environmental impact assessment tool must be capable of dealing with imprecise data and must be able to conclude under uncertainty. An adequate method for the mathematical modelling of processes which deal with uncertainty is *Fuzzy-Logic*. In a classically set theory, the membership of an object x to a set A out of a class X is defined by the two values 1 if x belongs to A: $x \in A$ and 0 if $x \notin A$. In a fuzzy set theory, a set A is characterised by a membership function $\mu : X \rightarrow [0,1]$ which assigns a grade of membership to the set A ranging between zero and one to each object $x \in X$. This property of fuzzy sets can be useful in environmental impact assessment. The transition from favourable to unfavourable environmental conditions for a receptor, for example, is often not crisp but fuzzy. The notions and operators of classical logic have been extended to fuzzy sets within the theory of fuzzy logic allowing approximative reasoning under uncertainty (Yager et al., 1992). The theory of Fuzzy-Logic is outlined in Zadeh (1965).

One of the first applications of fuzzy logic in modelling social systems with non–measurable variables was presented by Seppelt (1995). This work set up the base for the development of indicator systems based on fuzzy logic as described in Ludwig (1995). Based on these principal ideas, a generalised exposure-response model using fuzzy logic was developed to assess the environmental effects of the calculated immissions. Figure 2 shows the structure of the generalised model. The use of the fuzzy set theory in expert systems not only allows

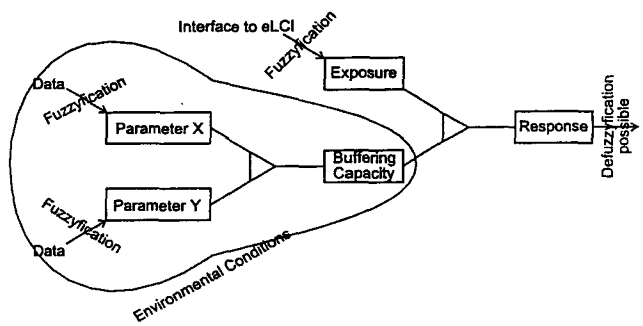

Fig. 2: Structure of the generalised fuzzy expert system

the use of crisp values from LCI as input variables. Linguistic terms can also be used in the data-base. This is an important advantage, especially in ecological assessment.

In the first step, the sensitivity of a receptor to a certain exposure is defined by a *buffering capacity*. This concept is well known in soil science and agrochemistry where it means the capability of the soil to neutralise acid input or a withdrawal of nutrients (Richter, 1986). For the integrated approach, we generalised this concept. The buffering capacity takes into account that a certain ability of the receptor exists to buffer exposures in most of the exposure-response relationships without showing any measurable effect. The buffering capacity depends on regional characteristics. In Fig. 2, the sub-model which calculates the buffering capacity is shown in the ellipse named *environmental conditions*. Here, the two parameters X and Y represent environmental characteristics and determine the buffering capacity. The sub-model for the calculation of the buffering capacity is applied to the different impact categories as for example soil acidification or eutrophication. The interdependance of the environmental characteristics and the buffering capacity has to be deduced from expert knowledge.

In the second step, the possible response of the receptor is assessed by a comparison of the buffering capacity with the immission values. If the immission values exceed the buffering capacity, a measure is derived for the potential ecological impact of the immission.

The environmental assessment is performed by fuzzy expert systems in the integrated LCA approach. In Fig. 2 the squares represent variables whose different expressions are defined by fuzzy sets. The triangles represent rule nodes. A typical rule could be: '*if parameter X is low and parameter Y is low, then the buffering capacity is low*'. The membership functions of the generalised response variable are defined as follows: If the membership degree of the fuzzy-sets of 'no effect' and 'low' are equal, then the defuzzyfication of the result by centre of gravity leads to the value 0 (→ *Fig. 3*). The response variable can easily be adapted to different receptors by rescaling of the

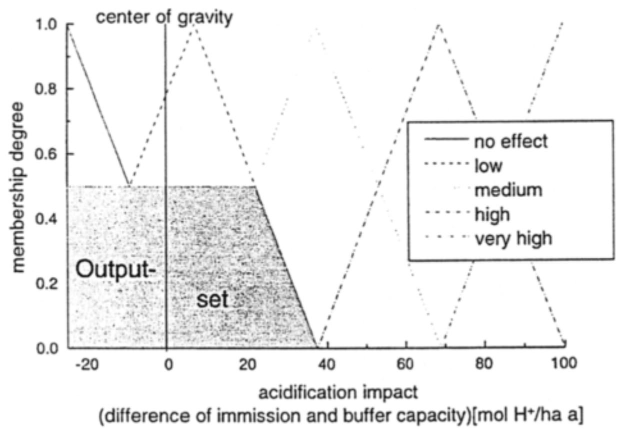

Fig. 3: Membership functions of the response-variable soil-acidification

x-axis. Adequate units for the x-axis should be chosen so that defuzzyfication leads to crisp values which represent determinable effects.

The fuzzy-sets of the immission, the buffering capacity and the response variable are defined in connection with the rule node in a way that, when the immission exceeds the buffering capacity, this leads to positive response values (i.e. negative effects). In the opposite case, the output of the response variable is '*no effect*'.

There are two alternatives for the interpretation of the resulting output:

- The first possibility is to have the output as linguistic variables. As the resulting output the fuzzy-set with highest membership value is chosen. This could, for example, be: *possible damage is 'very high with the membership degree 0.6'*.
- The second alternative is a crisp value after defuzzyfication. This is a theoretical value which represents the difference between immission and buffering capacity. Hence the impact on the receptor can be quantified and model estimates can even be evaluated in on-site measurements.

Box 1 summarises all applied rules and development steps for the set-up of the generalised fuzzy expert system. The observance of all above described criteria leads to transparent and plausible conclusions within the Fuzzy-Expert-Systems[2].

4 Prototype Case Study

The following section sheds some light on the application of the above presented modelling and assessment concept.

4.1 Definition of goal and scope

The approach was applied to the life cycle of car components of Volkswagen Polo®, produced by the Volkswagen AG. A Life Cycle Inventory has been realised for the planned production of magnesium-door-parts using the annual Polo production chiffres in Wolfsburg of 1995. The environmental fate modelling focused on the fate of emitted nitrogen oxides as they cause several typically regional or local impacts. In the environmental assessment of the NO_x-emissions, the possible response of the three receptors crop, soil and ecosystem were assessed.

For the development of the LCIA fuzzy expert systems the following rules are used to minimise the number of free parameters in the fuzzy expert systems:

- definition of five fuzzy-sets with normalised membership-functions per variable: sets from 'very low' (respective to 'no effect' for the response-sets) up to 'very high' (see also *Fig. 3*)
- sum of all membership values over all fuzzy-sets per variable equals one
- definition of the membership-functions in a way that one value can belong at most to two different fuzzy-sets
- use of minimum-operator for modelling of an 'and'-connection in the premises
- use of maximum-operator for modelling of an 'or'-connection in the premises
- use of Mamdani-implication for the conclusion procedure: $I_{MAM}(x,y) = \min(x,y)$
- use of sup-min-operator for the propagation
- (if desired:) final calculation of a crisp value ('defuzzyfication') by the centre-of-gravity-method

Box 1: Rules and development steps for the element of the fuzzy assessment model

4.2 LCI of production of magnesium-door-parts

The following processes were investigated in the LCI for the planned production of the magnesium (Mg)-door-parts:

- raw Mg-production
- production of the alloy Mg-AM 60
- smelter
- die casting
- part finishing
- chromate treatment
- recycling of the production residues (leading to input of secondary Mg-AM 60 in the smelter)
- transportation between the different production sites as well as the recycling facilities.

The Mg-production and alloy production take place in Israel, the other processes from smelter to chromate treatment take place in Germany. The data for the production activities were provided by Volkswagen. The transportation processes between the production sites were calculated using databases from the underlying LCI tool Umberto. The portion of secondary Mg-AM 60 input in the smelter was assumed to be 24.7%.

[2] For the integrated LCA approach we have used the fuzzy tool Fuzzy-Control-Manager® (FCM).

NO_x-emissions are chosen for detailed study: The results of the LCI show that more than 80 % of the NO_x-emissions are released in the first two processes at Dead Sea Works in Israel. The remaining NO_x-emissions occur at energy production sites in Germany (16.8%) and in other operations (1.9%). The high share of NO_x-emissions in Israel is mostly due to the fact that at Dead Sea Works the energy demand is covered by a power plant burning residual oil. The power plant is located in Israel at the southern end of the *Dead Sea*. Hence, we focused our attention on the environment of this site in the environmental fate modelling. The emission results of the LCI yield the input flow of the reaction-dispersion model. We made calculations for the annual Mg production of approximately 30000 t at Dead Sea Works. The annual demand due to VW-Polo production is only about 8.2% of this amount. However, to estimate the potential impact of the NO_x-emissions on the environment near the power plant, the calculations have to be based on the energy demand for the entire annual Mg production at this site.

4.3 Application of environmental fate modelling to NO_x-emissions

The environmental fate modelling of the emitted NO_x has been performed by a box–model approach (see Fisher & Smith, 1987; Russell, 1988). The emission smoke plume is numerically separated into several discrete compartments with a trapezoid surface (x and y-axis) and a constant height of 1000 m (z-axis). The trapezoid surface takes into account the increasing width of the plume (as a function of the distance to the emission source). The limitation to the height of 1000 m is due to the observed mean height of the boundary layer (Stull, 1988). This limitation of the boundary layer is caused by a temperature inversion in the lower troposphere. The inversion has the effect of an exchange barrier between the atmospheric layers above and below.

Most frequent meteorological situations based on long term meteorological mean values set up the base for reaction dispersion modelling scenarios. Furthermore, different scenarios can be defined by possible future production of the car components. For detailed study, production is assumed to be constant and different meteorological scenarios are defined.

Stack emissions are approximated assuming a continuous operation of the power plant. Mean wind speed and direction for the site are taken from Adler (1985). Dispersion was calculated with discrete time steps of 1 hour.

Chemical reaction and deposition are calculated for each numerical compartment of the plume. **Figure 4** shows the chemical reactions and substances which are taken into account.

The chemical reactions and deposition processes are modelled based on an ordinary differential equation system (ODE). The box–model simulates the matter transport via a successive numerical solution of the initial value problem. Initial values for the background concentrations were taken from Krüger & Graßl (1994). Chemical reactions are a function of ambient temperature and concentrations. Parametrisation of those functions is according to Simpson et al. (1990) and Krüger & Graßl (1994). Deposition rates are assumed to be constant. They were taken from Grennfelt (1987) and Krüger & Graßl (1994). A practical assumption for long-term prediction in the considered dry region is, to aggregate wet and dry deposition to a total deposition rate. Properties of the boundary layer are different for day/night and winter/summer. Box 2 summarises all model equations, parameters and background concentrations of the model. Note that the ODE system is run for each box-compartment. Convection/Dispersion is modelled by the general initial condition, which hands over the concentrations to the following box-compartment.

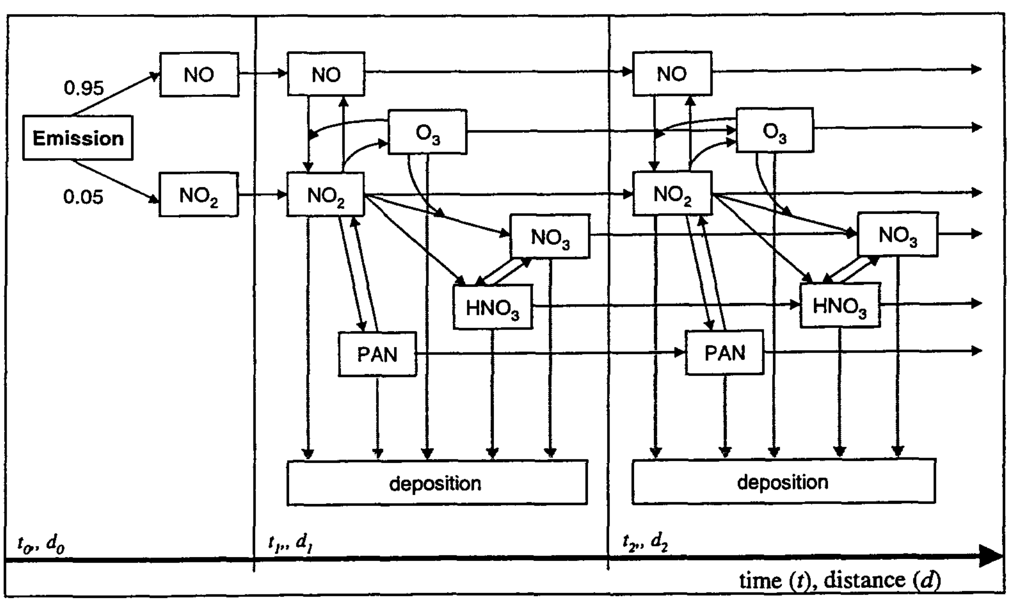

Fig. 4: Chemical reactions and deposition processes in the NO_x dispersion reaction model

General Notations

$C_{x,k}(t)$	concentration in [mol/cm³] of substance x in compartment k = 1, 2, ...
V_k	Volume of box-compartment k [cm³]
t	time in [h]
T	Temperature [Kelvin]
k_x	reaction coefficients
d_x	deposition rates [l/h]
α	zenith angle of sun

Equation System for each compartment k (index not printed)

$$\dot{C}_{NO} = k_{NO_2\,NO}(t)C_{NO_2} - k_{NO\,NO_2}(T)C_{NO}C_{O_3}$$

$$\dot{C}_{NO_2} = k_{NO\,NO_2}(T)C_{NO}C_{O_3} + k_{PAN\,NO_2}(T)C_{PAN} - \left(k_{NO_2\,NO}(t)k_{NO_2NO_3}(t,T)C_{O_3} + k_{NO_2HNO_3}[OH\cdot] + k_{NO_2PAN}[CH_3COO_2\cdot] + d_{NO_2}\right)C_{NO_2}$$

$$\dot{C}_{HNO_3} = k_{NO_2HNO_3}[OH\cdot]C_{NO_2} + k_{NO_3HNO_3}C_{NO_3} - (k_{HNO_3NO_3} + d_{HNO_3})C_{HNO_3}$$

$$\dot{C}_{PAN} = k_{NO_2PAN}C_{NO_2}[CH_3COO_2\cdot] - (k_{PAN\,NO_2}(T) + d_{PAN})C_{PAN}$$

$$\dot{C}_{NO_3} = k_{NO_2NO_3}(t,T)C_{NO_2}C_{O_3} + k_{HNO_3NO_3}C_{HNO_3} - (k_{NO_3HNO_3} + d_{NO_3})C_{NO_3}$$

$$\dot{C}_{O_3} = k_{NO_2NO}(t)C_{NO_2} - (k_{NO\,NO_2}(T)C_{NO} + k_{NO_2NO_3}(t,T)C_{NO_2} + d_{O_3}(t))C_{O_3}$$

General Initial Condition

$$C_{x,k+1}(0) = C_x(0) + \frac{1}{V_{k+1}}C_{x,k}(t)V_k\left(1 - \frac{C_x(0)}{C_{x,k}(0)}\right)$$

Background Concentrations and Deposition Rates (KRÜGER & GRASSL, 1994; GRENNFELT, 1987)

substance x	NO	NO_2	PAN	HNO_3	NO_3	O_3	
$C_x(0)$	0.987	1.93	0.196	0.654	1.88	18900	10^{-17}mol/cm³
d_x		0.036	0.144	0.0072	0.0036	0.018 (daytime)	[l/h]
						0.0018 (at night)	

Coefficients (KRÜGER & GRASSL, 1994; SIMPSON et al., 1990)

$$k_{NO\,NO_2}(T) = 7.56\ 10^{-9}e^{-1450\frac{1}{T}}\ [\text{cm}^3/\text{mol/h}]$$

$$k_{NO_2NO}(t) = \begin{cases} 18e^{-0.39\frac{1}{\sin(\alpha)}} & \text{daytime} \\ 0 & \text{else} \end{cases}\ [\text{l/h}]\ \text{(desert area)}$$

$$k_{NO_2PAN} = 1.15\ 10^{-8}\ [\text{cm}^3/\text{mol/h}]$$

$$k_{NO_2HNO_3} = 3.96\ 10^{-8}\ [\text{cm}^3/\text{mol/h}]$$

$$k_{PAN\,NO_2}(T) = 2.7\ 10^{18}e^{-12530\frac{1}{T}}\ [\text{l/h}]$$

$$k_{NO_2NO_3}(T,t) = \begin{cases} 8.64 10^{-10}e^{-2450\frac{1}{T}} & \text{at night} \\ 0 & \text{else} \end{cases}\ [\text{cm}^3/\text{mol/h}]$$

$$k_{HNO_3NO_3} = 3.6\ 10^{-2}\ [\text{l/h}]$$

$$k_{NO_3HNO_3} = 1.8\ 10^{-2}\ [\text{l/h}]$$

	day [OH·] [mol/cm³]	day [CH_3COO_2·] [mol/cm³]	day T [Kelvin]	night [OH·] [mol/cm³]	night [CH_3COO_2·] [mol/cm³]	night T [Kelvin]	α solstice
summer	2.67 10^{-10}	4.78 10^{-18}	308	2.62 10^{-20}	4.35 10^{-19}	298	82.5°
winter	2.32 10^{-18}	6.67 10^{-18}	291	2.32 10^{-20}	6.6 10^{-19}	282	35.5°

Box 2: Summary of ordinary differential equation system for reaction diffusion simulation of NO and NO_2 emissions

Results of this simulation are long-term forecasts of concentrations and immissions. Long term forecast is here understood as annual mean values in the time range of several years. **Figure 5** shows the results of the environmental fate modelling given as concentrations in the plume. To demonstrate the difference in the reaction dynamics in winter and summer, the corresponding graphs are juxtaposed. Windwards of the stack (left portion in *Fig. 5*) the daily variation of the background concentrations can be observed. Steady state conditions are presumed during the day and during the night. Leewards of the stack (right portion in *Fig. 5*), the plume's influence on the atmospheric concentrations of the considered substances is shown. The NO_x-concentrations near the stack are significantly higher than the presumed background values. Nevertheless, the NO_x-concentrations caused by magnesium production do not exceed the average NO_x-concentrations of Jerusalem, a NO_x-burdened site in Israel (Luria et al., 1985). About 250 km leewards of the stack, the NO_x-concentrations are almost down to the background level again. Note that in summer due to higher temperatures and due to a higher level of oxidants (e.g. ozone), the reactions are faster than in winter.

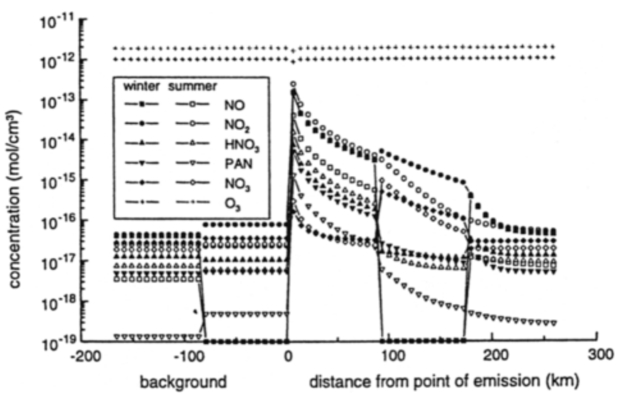

Fig. 5: Results from long term forecasts of concentrations and immissions. For a comparison of the climatic situation of winter and summer, the corresponding graphs are juxtaposed: winter: dark dots, summer: white dots

For the subsequent environmental impact assessment step we used mean concentration and deposition values which were derived of the different winter/summer and day/night scenarios.

4.4 Environmental Impact Assessment: Fuzzy–Expert–Systems

Out of the generalised fuzzy expert system presented in section 3.3 we developed three models to assess the impact of immissions on the ecosystem characterised by selected indicators. The selected indicators are plant damage, soil acidification and eutrophication.

4.4.1 Soil Acidification due to NO_x

Here we present in detail the model for soil acidification caused by NO_x. It is based on an expert system developed by Kuylenstierna et al. (1995). The fuzzy expert system is illustrated in **Figure 6**. In this model, average soil pH-values and ambient precipitation/evaporation indices determine the buffering capacity of the soils.

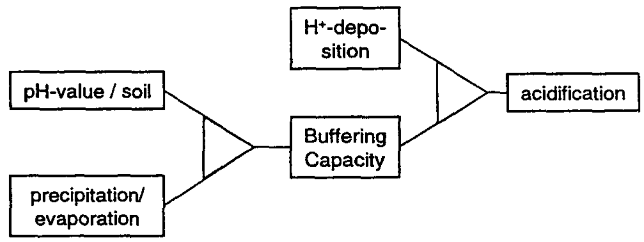

Fig. 6: Structure of the fuzzy expert system for soil acidification

High pH-values of the soil obviously result in a high buffering-capacity. A low precipitation/evaporation index also leads to a high buffering capacity. This is due to the fact that we primarily observe ascending movements of the soil-water in semiarid or arid regions which lead to an increase of Calcium-Carbonates in the upper soil-horizons. This eventually contributes to the development of Pedocals (Eyre, 1968). A high deposition of protons (acids) and low buffering capacities leads to a high acidification impact and vice versa.

Figure 7 shows the result of the case study employed on the fuzzy expert system for soil acidification. In this scenario, the impact for wind direction north-west is calculated which means that the plume spreads in a south-east direction of the stack. Data for the environmental conditions is taken from Adler (1985). Units in this figure are lg(mol H^+/ ha a) for the H^+-deposition, lg[H^+] for the pH-value, dimensionless (mm/mm) for the precipitation/evaporation index and mol H^+/ ha a for the possible impact. Here, the impact is always below 0, which means that the H^+-deposition due to the NO_x-emissions caused by the power plant is below the buffering capacity of the soil. This example illustrates the high sensitivity of the model to changes in the environmental conditions. From km 30 to km 50, the plume traverses the Jordan mountainous region. The soils of this region are slightly more acidic than the soils in the Jordan Valley and east of the mountains. The values for the possible acidification-impact change with the soil-pH.

The calculations for the other 7 directions also lead to the result that the H^+-deposition due to the NO_x-emissions caused by the power plant is below the buffering capacity of the soil.

4.4.2 Eutrophication due to NO_x

The fuzzy expert system for eutrophication is based on the critical loads concept (see Nilsson et al., 1986). In this model,

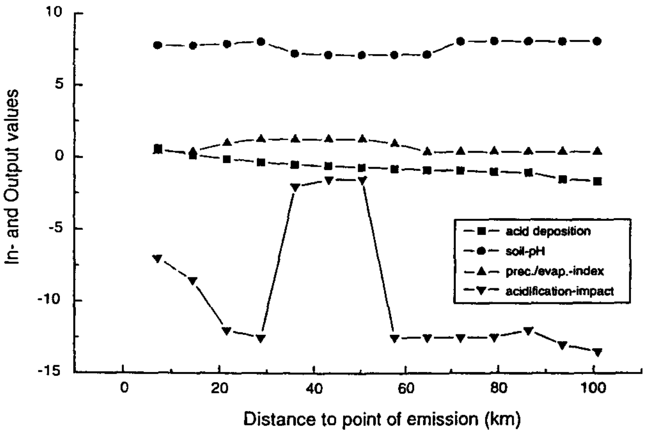

Fig. 7: Possible soil-acidification impact in the scenario "South-East of the stack" (see text for explanation of input and output values)

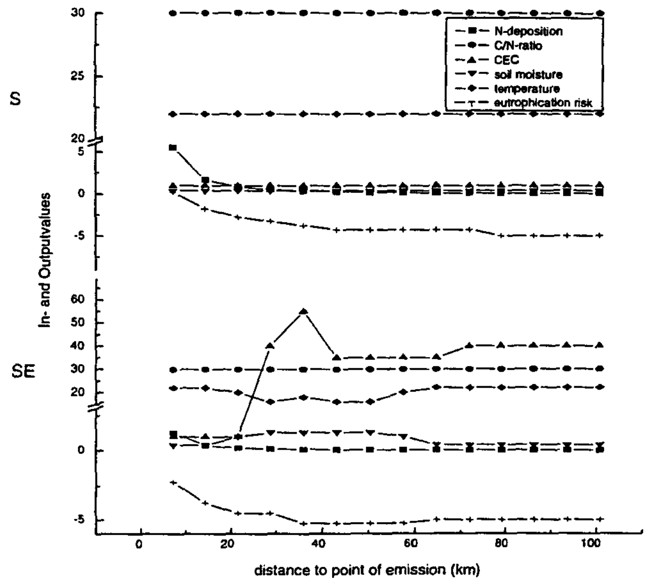

Fig. 8: Possible eutrophication impact in the scenario "South (upper part of figure) and South-East (lower part of figure) of the stack" (see text for explanation of input and output values)

the different soil characteristics cation exchange capacity (CEC), moisture, temperature and C/N ratio determine the main N-buffer biomass, denitrification and humus. In the model, the capacity of the biomass to buffer an additional N-input is determined by the application of the minimum principle of Liebig. The capacity is limited on the one hand by the CEC, which represents the availability of nutrients and on the other hand by the precipitation/evaporation index, which indicates the availability of soil water. A high precipitation/evaporation index and a high CEC have a positive effect on the biomass buffer and vice versa. The denitrification performance of the microorganisms is influenced by the temperature and the precipitation/evaporation index. High values of both factors lead to a good denitrification performance. The immobilisation of nitrogen within the humus fraction is increased by a high C/N-ratio and vice versa (Gundersen, 1992).

The three N-buffers determine the buffering capacity of the ecosystem with respect to nitrogen input. Supplementary N-input by microbiological fixation of N_2 is not considered (according to Posch, 1993). The loss of nitrogen by leaching is negligible due to the aridity of the regarded region (see Noy-Meir & Harpaz, 1977).

The model for eutrophication of soils forecasts low impacts which are negligible. The predicted ecological effects in this model also show a high sensitivity to the variability of soil characteristics across the Jordan mountainous region.
This is illustrated in **Figure 8**. In the upper part of the figure, the results are shown for the possible impact south of the stack. In the lower part, the assessment results south-east of the stack are indicated. The values for the environmental conditions are taken from Adler (1985). In Figure 8, the N deposition is given as total N (in kg/ha a), the C/N ratio and the precipitation/evaporation index are dimensionless, the CEC is given as meq/100 g soil. The unit for the mean ambient temperature near the soil is °C. The possible eutrophication impact is given as kg N/ha a. It represents the difference between N-deposition and buffering capacity.

Eutrophication impacts for the other 6 directions are negligible. This is mostly due to the fact that the wind regime is dominated by the wind directions north and north–west and therefore the highest NO_x-immission values are south and south–east of the power plant.

4.4.3 Plant Damage due to NO_x

NO and NO_2-immissions can have adverse effects on the development and physiology of plants (Sanders et al., 1995). However, as nitrogen compounds are also nutrients for plant growth, low doses of NO_x can lead to positive effects on plants (Curtiss & Rabl, 1996). Within the Fuzzy expert system for possible plant damage, three different fuzzy sets have been defined for the susceptibility of plants to NO_x. These sets represent the dose response relationships of the three plant categories of very susceptible, susceptible and less susceptible to NO_x-immissions. The threshold values for adverse effects due to NO_x-immissions have been defined in accordance to Kolar (1990) as follows: very susceptible plants: 100 µg/m³ (given as mean value in 6 months time), susceptible plants: 160 µg/m³ and less susceptible plants: 250 µg/m³. The possible nutritional effect of low NO_x-immissions has been taken into account within the fuzzy expert system.

In the first step of the environmental impact assessment for possible plant damage, the different crops in the vicinity of the power plant (up to 250 km distance) are assigned to their respective fuzzy sets of susceptibility and their response to the NO_x-immissions is estimated in the second step.

The model for plant effects forecasts a slight increase of potential crop yield south of the power plant. The effects in the other 7 directions for which calculations have been made are negligible.

5 Discussion and Outlook

LCIA faces spatial and temporal difficulties as well as problems concerning threshold values and dose-response relationships for many impact categories. In order to achieve a more extensive and accurate environmental assessment of product systems, the combined use of relative assessment techniques such as LCA and absolute assessing techniques like environmental fate modelling and environmental impact assessment, is a solution (DE HAES et al., 1998). To further investigate the advantages and difficulties of such an integrated approach, we have employed an environmental impact assessment in conjunction with LCA.

As a result of the methodological extensions and the application of a regional impact assessment for improving the accuracy of LCIA discussed above, the following conclusions can be made:

- An important methodological extension is the coupling of *heterogeneous mathematical modelling* developments: Petri–Nets for technical systems, ODE or even partial differential equation systems for reaction dispersion modelling and fuzzy expert systems for indicator development and assessment.
- This methodological extension allows the integration of different kinds of *information*: technically measurable data in LCI, chemical reactions and spatial spread which is often difficult to measure, as well as ecological impact assessment which is based on expert knowledge and is difficult to quantify.
- The first two steps of the integrated approach allow the derivation of indicator systems which *assess spatial heterogeneous ecological situations*.
- The approach circumvents one of the major limitations of LCIA. It can now address actual impacts at the site of emission, for instance the observed power plant. The suggested solution integrates absolute environmental assessment techniques into LCA.

The modular structure of the integrated approach and the well-defined interfaces between the three parts allow the exchange and improvement of each module separately. For instance, it is necessary to expand the model of environmental fate for other substances with their reactions or for a more complex geometry in other landscapes. An application of the described approach to other impact categories needs an extension of the fuzzy expert system. The use of fuzzy expert systems for assessment allows the possible input of linguistic data. An important feature for ecological and non–measurable data basis.

Further development should focus on these regional aspects. The use of geographic information systems allows the exchange of information and data between the three modules. Spatial information can also be used to support the fuzzy expert system. An integration of the described approach into a GIS should support diffuse, mobile and point sources of emissions from LCI. A regional decision system for the environmental impact assessment of anthropogenic emissions should therefore consist of the four elements LCA, fate modelling, assessing expert systems and Geographic Information Systems.

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